ENTROPY AS A TANGIBLE CONCEPTION

ENTROPY AS A TANGIBLE CONCEPTION

AN ELEMENTARY TREATISE

ON THE

PHYSICAL ASPECTS OF HEAT, ENTROPY, AND THERMAL INERTIA

FOR

DESIGNERS, STUDENTS, AND ENGINEERS

AND PARTICULARLY FOR USERS OF

STEAM AND STEAM CHARTS

BY

S. G. WHEELER, Eng. Lieut.-Commander, R.N.

Lecturer in Engine Design, Royal Naval Engineering College, Keyham, Devonport

LONDON

THE TECHNICAL PRESS LTD.

1921

PREFACE

This little book was written primarily for the use of lecturers and students, but it should appeal also to that wider circle of Engineers, Designers, and others who have already studied the subject on which it briefly touches, and have become familiar with the various problems, processes, and truths to which it refers, as actualities of frequent occurrence and practical contact rather than as mere theories.

The book has been written with the idea of supplementing, not superseding, the ordinary textbook, and although in places a certain amount of overlap has occurred in this respect, it has been avoided wherever it has been considered possible.

In certain cases the overlap is intentional, and no apology is made, for instance, in the case of the somewhat elaborate emphasis on the distinction between Total or Added Heat as usually understood and heat which must be regarded as " Added " under certain technical conventions, and in particular when dealing with tables and charts or diagrams of the working substance of an engine.

Such conventions are fundamental to the whole science of thermodynamics, and it is the lack of appreciation of such points as these that affords the real stumbling-block to the

beginner rather than anything difficult in the physical problems and truths the significance of which he has to conceive

Conventions of this sort have therefore been intentionally laboured and elaborated and if in the elaboration some slight repetition of fundamental ideas has been found necessary, the importance of the subject dealt with should afford sufficient excuse for it

This part of the book is intended more particularly for beginners The analogy of heat energy with ordinary kinetic energy however and the deduced analogies which form perhaps the chief theme of the book should appeal to those more familiar with the subject as well

The subject of entropy in particular is perhaps a somewhat difficult one to grasp and even amongst the habitual users of steam charts or tables there may be many who make use of this property or quantity without any real conception of its significance and it is hoped that this little work may be of some use to these as well as to students and others who have had less practical experience

Finally the author's best thanks are due and he takes this opportunity of offering them to the very good friends who despite the pressure of other work have helped not only with a great deal of valuable criticism but also in the production of the book itself and in the possibility of presenting it to the press

S G W

June 1921

CONTENTS

ENTROPY AS A TANGIBLE CONCEPTION

I. Introductory.

Of all sciences of really modern growth there is probably none that presents more difficulty to the beginner than the extremely modern one of thermodynamics.

That this is partly due to the number of different theories that sprang up round its early days is possible, and perhaps excusable, but that the difficulty is principally or even very considerably due to these differences is not at all so evident as that it has been increased out of all proportion by the maze of intricate mathematics that has grown up round, and in most cases overgrown, the theories on which, whether they have been justified or not, the science of thermodynamics has at length developed.

The number of theories was no doubt inevitable from the fact that the heat engine became a commercial reality before thermodynamics was more than a mere potential scientific possibility, but the difficulty to most beginners lies not so much in the number or even in the apparent

divergencies and contradictions of theory as in the lack of appeal in an elaborate mathematical argument

Even now when the original theories have crystallized into something more or less uniform, the appeal is still lacking and the suspicion or lack of conviction which anything but the very simplest of mathematics gives to the ordinary enquirer is only heightened by the dependence of the whole fabric of this rather difficult science on some imaginary cycle or some ideal conditions which can never really occur in any engine or in any circumstance with which the practical thinking man is familiar

In any mathematical argument there is in fact the very real possibility that the initial premises on which it depends and which it often so effectually conceals may be not merely difficult for the ordinary man to discover and keep in sight, but when followed up may lead nowhere, or even be found to be initially false

An unconditional acceptance of Carnot s Theorems (vide *Reflexions sur la puissance motrice du feu, et sur les machines propres à developper cette puissance*, par S Carnot, Paris, 1824) was indeed found difficult by such pure scientists as Clausius, Tyndall and Thompson in the early eighteen fifties, while as recently as 1902 in what was then facetiously called the " Battle of Entropy more modern thinkers such as Swinburne Perry, Lodge, Poincaré and others have agreed to differ over a less doubtful if more abstruse subject

It is little then to be wondered at that the ordinary mortal feels somewhat lukewarm in his thermodynamical convictions and gropes for something on which to stake his scientific faith, that shall be more tangible than a tissue of somewhat involved mathematics built up on Carnot's Cycle and a vague theory of reversibility which he does not understand.

In the discussion of 1902 referred to above, Planck is said to have settled the dispute by stating that "Entropy was the Logarithm of the Probability of a State."

It will be attempted in the few following pages to give a more tangible interpretation of this quantity or property, and the general heat properties, etc., on which it depends, and although such an interpretation may be no more accurate than that above, it is hoped that it will appeal more to the faculties and conceptions of the ordinary mortal as opposed to the mathematician, and while avoiding any statement involving mathematical error, that it will at the same time avoid any unintelligible mathematics.

It is hoped thus that the student with little or no mathematics will be able to follow the argument and to check it step by step with a facility which he would be unable to enjoy were it presented in mathematical form. More important than this it is hoped that without the use of any ideal cycles or conditions it may be possible to present in simple form a tangible working conception of heat and heat quantities, changes,

and phenomena as actually met with, rather than a knowledge of certain vague theories and theorems of thermodynamics which may have, and in fact usually have, no real counterpart in practice

II A Rational Interpretation of Heat Quantities and Phenomena without Reference to their Mathematical Aspect

For the purpose of clearness in presenting such an interpretation it will be convenient to start with a few elementary definitions and laws

Heat has been defined as a form of energy, but there is little doubt that it is a form of internal kinetic energy and hence like the forms of kinetic energy with which we are more familiar, it consists merely of the motion of the matter of a body

Of the exact form of the motion we have not much idea but we know that it is internal and at the same time it is probably extremely small If small however, it must be extremely rapid, for the energy due to it even in very small bodies may often be quite considerable

Many of the evidences and effects of heat are almost universally familiar and require no exact analysis to be realized and even measured If however the energy of heat is to be employed to its best advantage, it is important that some

more real conception of its nature should be obtained than is involved, at all events, say, in the vague sensation of "hotness," which is perhaps the only one that is at all generally held.

Temperature, which is the scientific name for the feeling of "hotness" referred to, is usually defined as the degree or intensity of heat. If however we accept the theory that heat consists of some form of internal energy of motion, then there is every reason to believe that temperature is some function of the rapidity of that motion, and that a body is hot necessarily means that in some way or other its particles are moving very quickly inside it. This internal motion extends of course to the outside surfaces of a body and the feeling of "hotness" which is experienced, in touching such a body with the hand, is in all probability due to the very rapid impact of the particles of these outside surfaces on those of the skin of the hand.

The effect on the skin is practically the same as can be produced by ordinary mechanical impact or strain. The blister, for instance, that one achieves in batting or rowing, the sting of a piece of elastic, and the abrasion and the feeling of pain that may be obtained from the very sudden impact of any quickly moving body, particularly when of light material, are none of them very far different from the corresponding discomforts which can be produced by either extreme heat or extreme cold, particularly when experienced locally in a similar way.

This, of course, is only a rough and perhaps not a pathologically accurate illustration, but there are other considerations based on more scientific grounds which all point to the same conclusion namely that all energy and in fact the whole material scheme of creation is ultimately reducible to a question of matter and motion and that heat is no exception to this general law, any more than sound or light, or even space and time

Accepting this general conclusion, then, Heat in a body may quite adequately be interpreted as a very small and very rapid internal motion in its molecules, and the amount of the heat may therefore be measured by the energy of the motion

The *First Law of Thermodynamics* states in brief that ' heat and mechanical energy are mutually convertible and there should therefore be two factors which go to make up " quantity of heat just as there are two factors which go to make up the more ordinary kinetic energy

The first of these factors we have seen is temperature, while the second depends on the mass, and the nature of the mass under consideration, and just as in more familiar cases rapidity of motion affords us a means of measuring the first factor of kinetic energy, so in this case temperature affords us a means whereby we can measure the first factor of heat and thence by reference to unit mass of some standard substance determine its amount

The advantage of such an interpretation is obvious, since it affords a physical conception of heat on lines which are already familiar.

III. The Significance of Thermal Motion.

From the preceding step it is no very wide stretch of the imagination to assume that there is some form of "inertia" or property of absorbing and acquiring the motion in any body receiving heat, just as there is inertia to any other form of motion which we can name.

We do not know exactly what is the particular form of motion which constitutes heat: in some cases indeed there is evidence to show that it consists of ordinary linear motion and impact but whatever the form of the motion it is fair to assume that the inertia belonging to that motion depends, as with more ordinary motion, on some definite property or properties of the body receiving it. Without knowing them therefore, we may safely define these properties as the Thermal Inertia of the body heated, on the understanding that they bear to "heat motion," whatever it is, a similar relation to that which mass and rotational inertia bear to linear motion and rotation respectively.

We know that in linear motion the inertia of a body depends on, and is measured solely by its mass, while in rotary motion it cannot be measured by mass alone, but depends on the disposition and distance of this mass from the

centre of rotation In symbols, in fact, rotational inertia is measured by the quantity mk^2, where k is the radius of gyration, and it is possible that some similar inertia function may be particularly applicable to heat

In the simple case of a rise or fall of temperature that occurs without change of state, where mass and specific heat afford one factor of the energy of the heat while temperature affords the other, since temperature corresponds to the velocity function, mass and specific heat must correspond to the inertia In this simple case therefore the product mass × specific heat affords a ready interpretation of what is meant by Thermal Inertia, and in such cases of purely "*Sensible*" heat the specific heat of the substance heated may be regarded as a measure of its thermal inertia per unit mass, corresponding for instance to ρ, the density in cases of ordinary linear motion, or to k^2 the moment of inertia per unit mass in simple cases of rotation

In the case of *Latent Heat* the product "mass" × "specific heat" no longer forms the second factor of measurement, since in this case there is a change in the physical state of the body heated and a certain amount of the energy supplied is therefore absorbed in bringing the change about The same conception of the nature of heat however can be made to apply to such cases, and quantity of heat can therefore be measured by the product of an inertia and a velocity function in the perfectly general case, provided we go one step further in the concep-

tion and imagine a thermal inertia which is capable of variation whenever latent heat is involved.

An analogy or an almost analogous case is perhaps the absorption of energy that occurs when a body revolving round a fixed centre in a uniform circular path is allowed to change its radius of motion without actually changing its speed of rotation.

As with a heated body work is done against the internal and other forces resisting any change of state, so in this case is work done against the centrifugal or other forces which keep the rotating body to its original circular path, and as in the one case the change of rotation may be represented entirely by a change in the radius of gyration or what may be called its rotational inertia, it is possible that in the other case a change of state may be entirely represented by a change of thermal inertia. Many of the changes that actually take place when a body is heated, may in fact be accounted for numerically in this way, and it is possible that the changes really consist of the acquisition of some wider degree of freedom of molecular motion, such as may occur in perfectly simple cases of rotation, while the fact that such changes may occur quite naturally in simple rotation may be used to explain the equally natural changes of state that occur in a heated body.

Imagine, for instance, a flat circular disc suspended vertically from a point in its circumference by a thin cord or wire by means of which

it can be spun round about a vertical axis, as shown in Fig. 1.

As it is speeded up this disc will first rotate about its original vertical diameter, which will

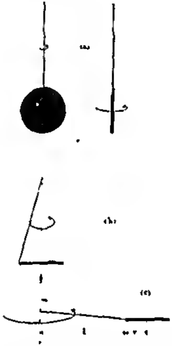


FIG. 1.—AN INSTANCE OF INCREASE OF ROTATIONAL INERTIA ACCOMPANYING AN INCREASE IN ENERGY OF ROTATION.

remain in line with the cord or wire as shown at *a* in the figure.

On the attainment of a certain speed however the disc as a whole will start to rise, the suspension cord making an angle with the original vertical diameter, which rapidly be-

comes more accentuated as more K.E. is added, till this diameter is horizontal and the disc is rotating about an axis through its centre and perpendicular to its plane, the centre remaining vertically below the fixed point of suspension, as shown at *b* in the figure.

A definite addition of K.E. is in fact accounted for by a definite increase of rotational inertia, since the mk^2 about the first axis is given by $mr^2/4$, and that about the second $mr^2/2$.

If the addition of K.E. is continued further moreover, at a still higher speed, the disc will quite suddenly begin to rise as a whole and to whirl at length about the point of suspension, the angle between the suspension cord and the disc becoming more obtuse till both are practically horizontal, as shown at *c* in the figure.

The addition of K.E. is in fact again accounted for by a definite increase of inertia, mk^2 in this third position being $m\left[\frac{r^2}{2} + (l + r)^2\right]$.

Now the increase in mk^2 or rotational inertia in both the definite stages denoted by the changes of disposition of the disc about its axis of rotation has been entirely due to the addition of K.E. supplied by twisting or spinning the suspension cord, and however carefully this spinning or twisting be done it is impossible to supply the additional energy without producing these changes of disposition, i.e. without altering the rotational inertia of the disc and cord considered as a whole.

The changes in the axis of rotation and conse-

quent changes in inertia of the rotating disc moreover occur at definite speeds as it receives energy, and it is not so improbable as at first sight it may seem therefore that the changes in form which occur at perfectly definite temperatures (as for instance when heat is added to ice to turn it to water, and to water to turn it to steam) may really take place in a similar manner by some corresponding change in disposition in the particular internal or ionic movement which we imagine to constitute heat, in other words that this motion may enjoy some form of increased freedom which may be regarded as an increase of thermal inertia

Whether this is actually the case or not it is practically impossible to say It is indeed little to be expected that the correspondence between ordinary heat changes and the changes in an ideal case of mechanical motion, whether rotary or otherwise is ever very exact, but in any case an explanation on these lines fits in roughly with the actual changes observed and in any case it is reasonable to assume that in the addition of heat there is a tendency to increase of some indefinite quantity of very much like these dimensions which is just as positive as the tendency to rise of temperature

Now *temperature* having been defined as a measure of the intensity of heat, or some function of the rapidity of heat motion in a body, and *thermal inertia* as the property of absorbing and acquiring this particular motion, if a body receive heat without a change in those properties

which constitute its thermal inertia it can only do so by a rise in temperature, and conversely the only way in which a body can receive heat when its temperature is constant is by an increase of what we have just called its thermal inertia, and this is a very convenient conception to have in the back of one's mind when dealing with the actual changes of heat and temperature that take place in the working substance in practice.

In rotation it is a familiar line of argument that if a body acquire energy with constant rotational inertia mk^2 it can only do it by an increase of speed, and conversely if it acquire energy without an increase of speed it can only do it by an increase in the quantity mk^2, and a very similar reasoning can be made to apply to heat and temperature.

There is *one proviso* however that must be made in applying such a system of measurement, viz. that the temperature must be an absolute measure of what we have referred to as the velocity factor, so that in combination with the inertia factor it may give an absolute measure of heat.

All measurements must therefore be made from the point at which heat and temperature may be supposed not to exist at all. The ordinary zeros on the centigrade and Fahrenheit scales obviously fail to satisfy this condition, since not only do they register two different points but temperatures much lower than either point have also been reached.

The reality of a point of no temperature and no heat is perhaps a little difficult to conceive, but its hypothetical position has been fairly accurately determined

It is assumed that if a body have no volume, it must also have no heat, and it is found that under any constant pressure all perfect gases, if reduced in temperature, suffer the same decrement of volume for the same reduction of temperature

The point, therefore, at which volume would vanish if it could be reached by a perfect gas is taken as the *absolute zero of temperature*, and there is the more justification for this in that at constant pressure the increase in volume of a perfect gas always gives a measure of any heat "received"

The position of the point referred to can obviously be determined by experiment, and accepted results give it as approximately 493 Fahrenheit degrees, or 274 centigrade degrees below the freezing-point of water under ordinary normal pressure Temperatures used therefore must be measured from this point i e $-461°$ F or $-274°$ C on the ordinary temperature scales, and with this proviso all the ordinary units will apply

IV. Thermal Inertia and Waste of Heat at Exhaust

Consider for a moment the working substance of a heat engine.

At the lowest available temperature the

maximum work will have been done, and the minimum waste that can occur is then the heat that is rejected AT THIS TEMPERATURE in the exhaust.

The exhaust waste therefore, if it is at constant temperature, is always given by the product of the thermal inertia at exhaust and the actual absolute exhaust temperature.

This follows at once from the definition of thermal inertia, for if thermal inertia is represented and measured by the symbol ϕ the heat added or rejected at any constant temperature is always given by the product ϕT, where T is the absolute temperature in question.

If the exhaust occurs at the lowest available temperature, this simple product is the minimum waste, and this is a most useful aspect of the property thermal inertia.

At a varying exhaust temperature the waste of course cannot possibly be a theoretical *minimum*, but its actual value will still be given by a succession of such small products (each considered at constant temperature) together with the heat due to the change of temperature alone.

As an analogy to minimum exhaust waste, suppose a shaft is only capable of doing work at or above a certain minimum speed; suppose for example that it can only be used for "boosting up" the power of another shaft always rotating at or above this speed.

Imagine that it can only be supplied with power from the energy of a rotating flywheel,

and thus can be connected up to it at will, say by some form of flexible clutch

With this arrangement, by giving up some of its speed, the flywheel can give up some of its energy to the shaft, and this can continue as long as its speed of rotation is slightly higher than the minimum speed of the shaft

It is obvious however that when once the speed of the flywheel has fallen to the minimum permissible speed of the shaft, it can do no further work on it whatever, and the energy that is left in it will therefore have to be wasted as far as the shaft is concerned

The waste of rotational energy in this simple imaginary case corresponds to the waste of heat in the exhaust of an engine as considered above

It is measured in a similar way by the product of an inertia and a speed function, which correspond respectively to thermal inertia and temperature while the minimum workable condition for the speed of the shaft corresponds to the lowest temperature available in the engine for exhaust

V THE COMPLETE PERFORMANCE OF A WORKING SUBSTANCE

The details of the simple arrangements described above require considerable modification and adjustment if the analogy is to be made to apply to the complete cycle of an actual working engine

In the first place the exchange of heat for work is not quite so simple and direct an affair as is imagined above, since heat, energy and work, however much interchangeable, are really two quite different quantities, and although it is usually easy to turn work into heat, it is not often at all easy to reverse the process.

In the second place the thermal inertia as we have defined it, is not a constant quantity, and as a matter of fact the transformation of heat into work does not as a rule take place without a change in this inertia.

For a better analogy, then, the mechanism should be more complicated, and the inertia should be capable of variation, as for instance in the case of the spinning disc referred to under Fig. 1.

With a mechanical device capable of variation in this way, the work done in any complete cycle could be represented at any instant is plotted against half the square of the rotational speed at that instant, i.e. a diagram in which mk^2 is plotted against $\frac{1}{2}\omega^2$.

Such a diagram would not only measure the work, but would represent it completely in terms of the energy of the mechanical working substance the changes in which have been at once the cause and the means of its performance.

A simple example of this is illustrated in Fig. 2, and provided we can visualize the changes in the working substance a similar diagram could be plotted for any change or process that we like to imagine.

There only remains, then, to determine the thermal inertia of any real working substance under the various actual conditions of pressure, volume or temperature, etc., with which we happen to be dealing, to be able to represent

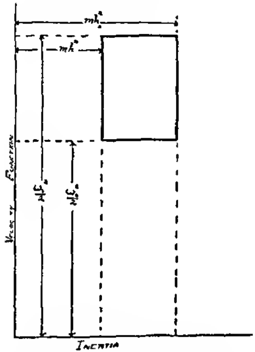


FIG 2—WORK DONE IN CYCLE OF OPERATIONS WITH MECHANICAL "WORKING SUBSTANCE."

the actual thermal performance of a heat engine done in any complete cycle of operations, and the heat changes in the working substance that have been necessary for its performance.

A mechanical device which very nearly repre-

sents this analogous change in a heat engine and therefore very nearly provides such a diagram automatically is described later and illustrated in Fig. 11. Before this can be properly understood however, it will be necessary to investigate in detail the thermal changes of an actual working substance.

VI. The Thermal Inertia of Water-Steam.

To actually calculate what we have called the thermal inertia of a working substance, and determine its numerical value for any given state or condition, we shall have to determine the heat that would be required to bring the substance to that state without variation of temperature from some point at the same temperature at which the thermal inertia may be considered to be known.

In the case of unevaporated water, as indeed with most liquids, provided there is no change of state, a definite increase of heat produces a definite rise of temperature. The thermal inertia of unevaporated water may therefore be considered to be known at all temperatures, its numerical value being determined from the increase of heat for the given temperature rise.

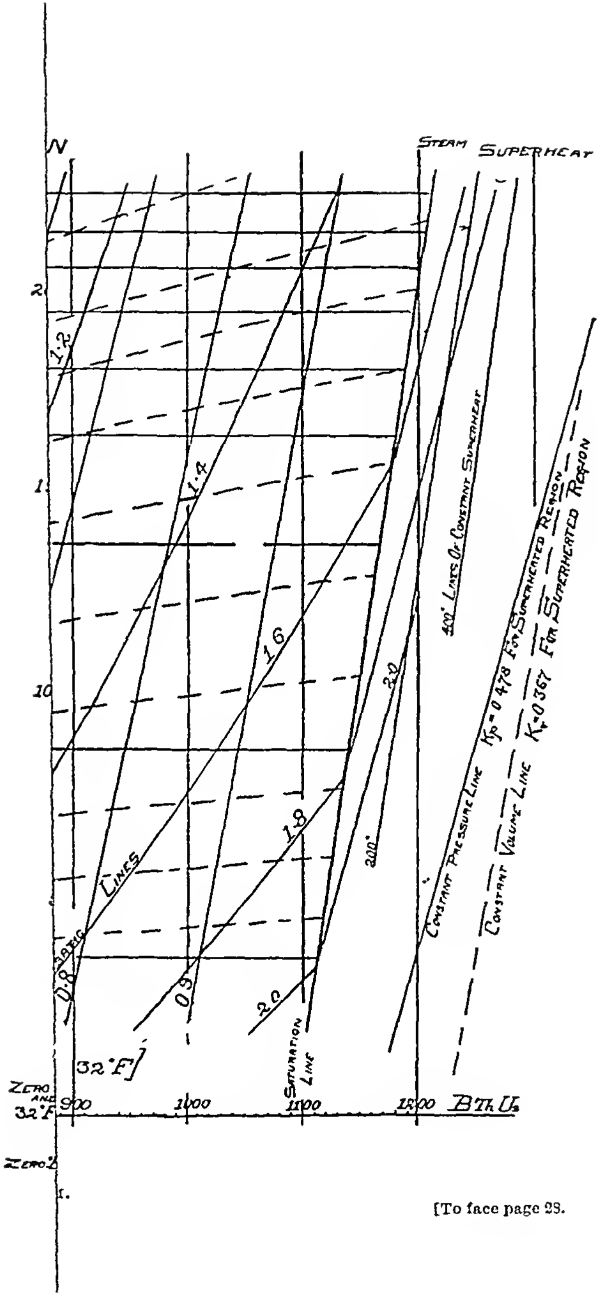
In the case of the working substance of the steam engine, therefore, i.e. in the case of water and its vapour, there remains only to determine the heat required to reach a given state or point

from that of unevaporated water at the same temperature, to be able to determine the thermal inertia of the working substance in any state or condition, and to assign to it a definite numerical value, which as part of a simple product with absolute temperature will enable us to measure heat in the ordinary units with which we are familiar

Now the heat that has to be added to water and steam under various different conditions is a quantity about which sufficient data is usually available for comparatively accurate calculations to be made, and these calculations once made can be tabulated for any case that we may wish to consider for future reference, and thus tabulated can be considered as heat properties of the water or steam in certain states or conditions just as its temperature or pressure

In certain simple cases these calculations and tabulations are already familiar, as for instance in ordinary steam tables giving the Total Heat, Sensible Heat, Latent Heat, External Energy, Volume and Temperature, etc, under conditions of constant pressure

Similar calculations can be made and tabulated for conditions of constant volume, or even of constant temperature, and with these conditions, by dividing the total heat by the absolute temperature at the point considered, the quantity that we have defined as thermal inertia can be readily and simply added to our tables.



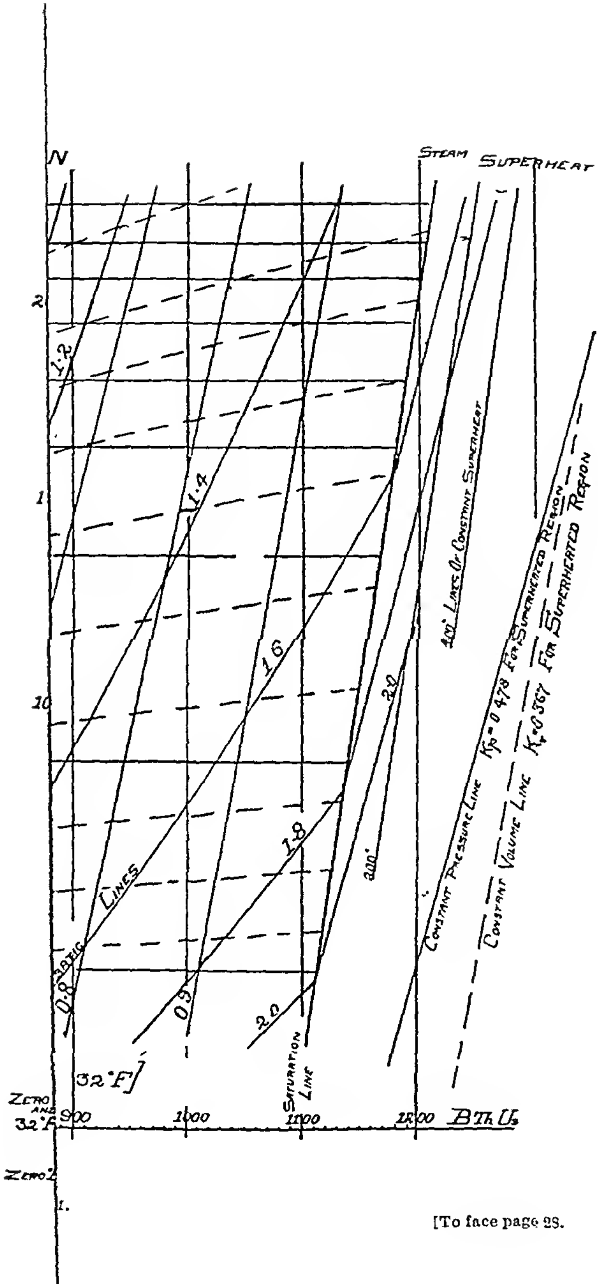
[To face page 28.

from that of unevaporated water at the same temperature, to be able to determine the thermal inertia of the working substance in any state or condition, and to assign to it a definite numerical value, which as part of a simple product with absolute temperature will enable us to measure heat in the ordinary units with which we are familiar

Now the heat that has to be added to water and steam under various different conditions is a quantity about which sufficient data is usually available for comparatively accurate calculations to be made, and these calculations once made can be tabulated for any case that we may wish to consider for future reference, and thus tabulated can be considered as heat properties of the water or steam in certain states or conditions just as its temperature or pressure

In certain simple cases these calculations and tabulations are already familiar, as for instance in ordinary steam tables giving the Total Heat, Sensible Heat, Latent Heat, External Energy, Volume and Temperature, etc, under conditions of constant pressure

Similar calculations can be made and tabulated for conditions of constant volume, or even of constant temperature, and with these conditions, by dividing the total heat by the absolute temperature at the point considered, the quantity that we have defined as thermal inertia can be readily and simply added to our tables.



[To face page 28.

VII. Steam Charts as Compared with Tables.

In modern practice it is more usual to represent all these quantities and calculations graphically in the form of charts. Such charts have obvious advantages in the interpolation of intermediate values and quantities which cannot be included in even the most elaborate and cumbersome tables. As far as the quantities themselves are concerned they involve no new idea however, and may be regarded simply as very complete lists of tabulated results, i.e. very complete steam tables presented in a graphical form.

A chart of this sort for the formation of steam at constant pressure is illustrated in Fig. 3, and it is seen that the total heat for instance, for various conditions of dryness, can be read off directly from the chart, whereas with tables it would require evaluation.

VIII. A Thermal Inertia – Temperature Chart

constructed on somewhat similar lines is shown in Fig. 4. The thermal inertia of water it will be seen is a constant quantity, and the inertia at other points on the chart is arrived at by adding to this quantity the additional inertia required to reach such points, at any constant

temperature, after starting from water at the same temperature, the additional inertia being calculated by dividing the heat required by the absolute temperatures in question.

In this chart it is seen that volume and other condition lines are included, which are very similar to those of the Total Heat – Temperature Chart of Fig. 3, and both this and the former chart can be regarded as a graphical presentation of ordinary steam tables, and each can therefore be used for tracing out the changes of the working substance during the whole or any part of its cycle of operations, just as the changes of rotational energy were traced out in the diagram of Fig. 2. In this connection it will be noted that in each chart the various adiabatic curves are given a numerical value which is referred to as the rank of their adiabasis or entropy, the meaning and exact significance of this quantity will however be described later.

The Thermal Inertia Chart has the advantage over the other in that it presents some sort of physical conception of the nature and extent of the changes that make a cycle of operations possible and necessary. It also has the very great advantage that its areas, from the definitions involved, are work or energy areas, while those of the Total Heat Chart of Fig. 3 have no particular significance.

The area enclosed by any complete path on the Thermal Inertia Chart in fact measures the work done in a complete cycle of operations of the working substance of the engine, just as

the area of the mechanical inertia diagram of Fig. 2 measures the work done in the mechanical analogy thus considered, and the changes that take place in the working substance of the engine may with some slight stretch of the imagination be regarded as similar to the changes in a corresponding diagram in the mechanical analogy, both in their extent and their nature, including their ultimate effect on the thermal performance.

It is convenient to represent thermal inertia by the symbol ψ, and heat being measured by the product of thermal inertia and temperature is therefore given by ψT, where T is the absolute temperature in virtue of which the heat may be considered to be "held," a temperature which corresponds possibly to half the square of some imaginary "heat speed" τ.

Similarly rotational energy is given by $\frac{1}{2}I\omega^2$ or $mk^2 \times \frac{\omega^2}{2}$, where $\frac{\omega^2}{2}$ is half the square of the rotational speed, i.e. of the angular velocity ω.

IX. Measurements of Thermal Inertia.

The ideal starting-point from which to formulate any system of heat measurement is obviously the point of absolute zero, and in the Thermal Inertia Chart of Fig. 4 the imaginary origin is therefore taken as the zero both of inertia and of temperature as indicated in Fig. 5.

Thermal inertia really measures both the

capacity of a body for heat and its awkwardness in turning heat into work, and is actually independent of any system of heat units, and depends only on the unit of mass, since both its numerator

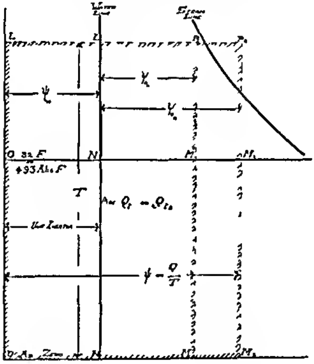


FIG 5—ψ T DIAGRAM MEASUREMENTS

and denominator involve the same unit of temperature

The Unit of Thermal Inertia is naturally "that inertia which in conjunction with unit changes of temperature will be responsible for and involve the unit change of heat"

In eases in whieh heat is aequired or rejected by change of temperature alone it is obvious and has alrcady been seen that thermal inertia becomes the simple product mass × specifie heat, and in such eases the unit becomes unit mass-specifie heat.

In the general ease of course the unit and the quantity itself require an extension of this coneeption to inelude proeesses involving a change of state or the performance of work both with and without a ehange of temperature. This however need not affeet the definition of aetual measurement, and sinee with reasonable aecuracy the speeifie heat of water may be taken as unity at all temperatures, it may be said with reasonable aeeuraey that unit mass of water, as such, has unit thermal inertia.

A suitable name for this unit would perhaps be a "heat slug," sinee it suggests the property of sluggishness, but sinee, as far as measurements are eoneerned, it has exaetly the same dimensions as the property known as "heat rank" in entropy, it is perhaps eonvenient to retain this name.

In any case the product 1 Rank × 1° F. produces 1 B.T.U., or in general terms, unit inertia × unit temperature = one unit cf heat, and the latter equation is true whether we call thc unit of inertia a "heat slug" or a "rank," and whether the temperaturc and heat are measured on the Fahrenheit or centigrade scale, or on any other, provided that the scales of heat, mass, and temperature eorrespond.

X A General Analysis of the ϕT Diagram

The heat that is measured direct by the product of thermal inertia and temperature is, as we have seen, the heat that may be said to be "held" by the thermal inertia of a body, and thus in its simplest case is the heat "at constant temperature," which we may denote by the symbol Q_t. With a similar nomenclature heat at constant pressure may be denoted by Q_p, and that at constant volume by Q_v, while that added in any process whatever may be denoted by the perfectly general symbol Q.

In some cases, as for instance in the addition or acquisition of sensible heat, the quantity Q_t becomes somewhat imaginary, and in such cases advantage must be taken of the fact that the thermal inertia of water is a known quantity. The imaginary quantity Q_t or the real quantity $\phi \times T$ may then be taken as (and in point of fact is always numerically equal to) the sum of the sensible heat required to reach the final temperature along the water line and the additional heat required to reach the actual state considered from water at the temperature in question.

The water line on the chart is therefore represented by a sensibly vertical ordinate at unit distance from the absolute axis of the chart, and starting from the point at which the water freezes as shown in Fig. 5. This line obviously

has no physical meaning if continued below the freezing-point, and although it would be possible to extend the chart to the region of ice, this would serve no useful purpose, since all our calculations deal with heat that is added to the water and steam well above this region.

The line of dry saturation is a sloping curve showing a varying thermal inertia for different temperatures, and if we consider only the excess of the thermal inertia of the steam over that of the water, it is obviously given in the saturated region by the latent heat divided by the absolute temperature. This is also shown in Fig. 5.

When measured from the water line in this way the quantity Q_t for any point, whether in the saturated or superheated region, is the sum of the latent heat and any additional heat that would be required for isothermal expansion at the temperature in question.

This quantity is always measured by the area of the rectangle as projected from the point on to the water line, i.e. by the area PLNM in Fig. 5.

When measured from absolute zero Q_t or $\phi \times T$ includes the sensible heat, and is measured by the complete rectangle up to the absolute axes, i.e. by the area PL′OM in Fig. 5.

From water at any other temperature the area of the complete rectangle PL′OM, minus the area representing the sensible heat up to the temperature in question, gives the quantity Q_t.

From water at 32° *F. or* 493° *Abs. F.* Q_t is therefore given by the area of the rectangle minus that of the constant rectangle ON.

Thermal Inertia may be measured from various starting-points in the same way, and it is sometimes convenient to consider the acquisition of inertia of steam as being made up of two parts, and consisting of steam inertia and water inertia as denoted by the symbols ψ_s and ψ_w, the total

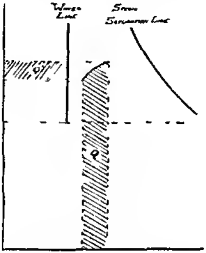


FIG 6 ADDED HEAT AREAS ON THE ψ T DIAGRAM

thermal inertia ψ at any point being given by the sum of ψ_s and ψ_w.

Heat or Work Areas

It follows from the above premises that at any point the quantity (of heat held by the water or steam in virtue of its thermal inertia at that point) is given in absolute units by the area of the complete rectangle drawn from the point in question to the absolute axes of the chart, and that this quantity and this

area can be considered to represent the heat actually added if the entire process is one of constant inertia along the water line and constant temperature elsewhere.

For any other process in general the actual added heat (subject to certain general limitations given below) will be represented by the sum of two areas, viz. the complete area vertically below

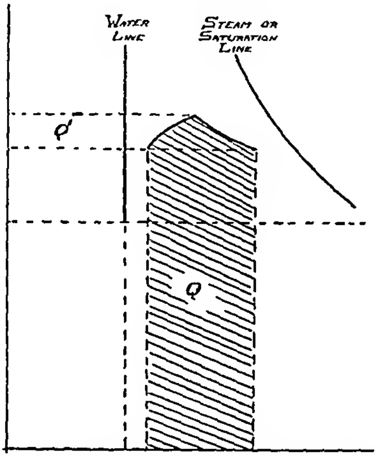


FIG. 7.—ADDED HEAT AREA WHEN STARTING AND FINISHING AT THE SAME TEMPERATURE.

the path representing any such process, and that part of the corresponding horizontal area intercepted between the absolute vertical axis and the water line, i.e. the shaded areas Q and Q′ of Fig. 6.

The part of the horizontal area that is left blank belongs to the product $\phi \times T$, but not to the general quantity Q. It represents the extra part that would have had to be added

to have reached the final state by the path of constant specific heat along the water line and constant temperature afterwards, that is specified in the definition of ϕ as Q/T. This constitutes a difference between thermal inertia and ordinary inertia, but as will be seen later, in most cases the difference is slight and in many cases vanishes altogether.

For a process starting and finishing at the same temperature, as shown in Fig. 7, the double area representing the actual added heat in the case of Fig. 6 may be simplified into the single vertical area Q, since the same horizontal area Q′ is always deducted on the fall of temperature as was added on its corresponding rise.

It follows that for any complete cycle or enclosed path, as shown in Fig. 8, the enclosed area W represents the work done, for within the same general limitations that apply to all charts the heat actually received is the complete area Q_1 below the upper half of the path, that rejected is the area Q_2 below the lower half.

The area W is the difference between these two, and is therefore the actual heat that is converted into work.

XI. Total and Added Heat.

The variety of different conditions under which heat may be acquired, employed or rejected by a working substance is naturally

infinite, and it is this that gives the steam chart the great advantage over steam tables.

We have already briefly enumerated three different conditions which are easily defined, viz. the conditions of constant pressure, constant volume, and constant temperature. The heat received or rejected under these conditions we have referred to respectively by the symbol Q_p, Q_v, and Q_t.

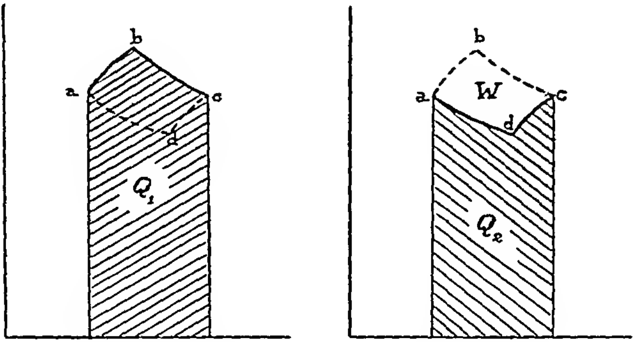


FIG. 8.—HEAT ADDED, HEAT REJECTED, AND WORK DONE IN COMPLETED CYCLE AS SHOWN ON $\phi - T$ DIAGRAM.

If measured from the proper starting-point the quantity Q_p is numerically equal to the sum at any instant of the internal and external energies of the body heated, i.e. to $I + \frac{pv}{J}$ employing the usual symbols. It is often referred to as the "Total Heat" of a body, or more fully the "Total Heat at Constant Pressure," and is usually denoted by the symbol H.

Similarly Q_v is often referred to as the "Total Heat at Constant Volume," and since in this

case no external work has been done and therefore no external energy created, it is numerically equivalent to the internal energy I at the instant considered.

Q_t we have already referred to as the energy held in virtue of the thermal inertia at this instant considered of the body heated, but under a similar nomenclature to the other two quantities it may also be called the "Total Heat at Constant Temperature"

Each of these quantities gives the heat added for a definite process under definite conditions, and it will therefore be seen that a change from one temperature to another or from one volume or one pressure to another may in certain circumstances require either one or another of these quantities, since it may almost always be effected under a choice of two of the constant conditions specified

If these conditions represented the only choice it would be possible, and sufficient to compile tables of the three quantities Q_p, Q_v, and Q_t for various ranges of pressure, volume, and temperature, and so compete with any change in the least likely to occur in practice

Unfortunately however the conditions specified do not even represent the ones that probably occur, and we have already seen that the possible variety is infinite

To compete with all possible variations of conditions therefore would require an infinite number of tables, generally different, and it would furthermore be necessary to be able to

transfer from one table to another, at will, whenever the conditions changed.

In a chart, on the other hand, it is seen that it is possible to pass from one state point to another by an infinite choice of paths, each path representing some slightly different condition under which the heat quantities can be measured, and as has already been seen the general process of measurement becomes a mere matter of reading off from a simple scale or an area which is almost as convenient for any one path as for any other.

Knowing the scales of area or of other measurements on a chart therefore, it is merely necessary to trace out the path, representing any condition or any change in order to be able to read off the heat received, rejected, and employed under the conditions considered, and thus to determine the work done, or any taking place during the change in question. Before however these scales and areas can be correctly interpreted under all conditions it will be found necessary to lay down certain limitations and definitions as to what may with fairness be regarded as "added," "acquired," or "rejected" heat in the perfectly general case.

XII. Conditions and Limitations Necessary in the Interpretation of "Added Heat."

In the general case whenever heat is added to or subtracted from a body, there are a number

of quantities which in their changes are capable of absorbing it or at all events accounting for it. Among these quantities are temperature, state or condition, pressure, volume, dryness, etc., and as a rule a definite addition or subtraction of heat will produce perfectly definite changes in these quantities, which are definitely interdependent on each other.

In the case of volume however a change may take place either accompanied or unaccompanied by the performance of work or the generation of an equivalent amount of kinetic energy or actual motion, and obviously, although two such changes may be identical in every other respect, they will be different with respect to the quantity of heat added, as well as the work done

As an example of this we may take the two parallel cases of throttling, and of perfectly resisted or perfectly unresisted jacketed expansion for the same ranges of pressure, volume and temperature, etc. Both cases are examples of expansion at constant "Total Heat" H, and both must therefore appear as exactly the same line on any chart, but in the one case the heat actually added is nil, while in the other it is sufficient for the performance of the whole work against the external resistance, or the whole of the K.E. generated, as the case may be

If however we include under "*added*" heat all that due to internal causes, such as friction, chemical action and combustion, etc., as well as the heat added externally in its more usually

recognizable form, it will be found that we shall have afforded a distinction between these two parallel cases, and have adopted a convention by which we shall be able without ambiguity to measure added heat, in general, from calculations based on tables and therefore to represent it on diagrams and permanent charts which will be applicable to any process and to any condition that we like to imagine.

Such a convention moreover makes the more complicated cases of jacketed and unresisted expansions comparatively simple for calculation, since even in imperfectly resisted or unresisted processes, if either the actual or proportionate amount of work done or K.E. generated is known, the actual externally added heat can be determined, since this will always be short of the heat conventionally "added," i.e. of that added in the corresponding perfectly resisted expansion by the deficit in the K.E. generated or work done.

XIII. "Added Heat" and Adiabatic Conditions.

It will be seen that the above convention is not unconnected with the considerations which lead to the definition of the conditions that are known as adiabatic.

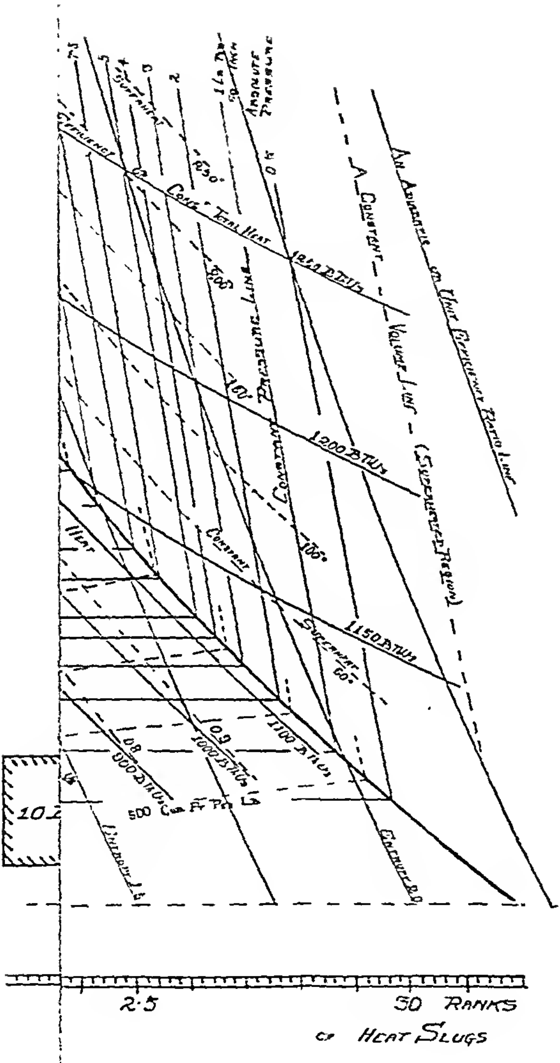
An old definition of an adiabatic change was "*one in which no heat is added or lost*," but unless these simple conditions are qualified by

the proviso that, as well as conforming to them, a true adiabatic change must be opposed at all points by a resistance sensibly equal to the working pressure, or, failing that, accompanied at each point by the generation of kinetic energy equivalent to the work that would result from such opposition, in other words, unless the change is either "perfectly resisted" or "perfectly unresisted" the definition will include any change that may occur without jacket heat and even such extreme cases as "wire drawing" or "throttling," provided they take place in properly non-conducting boundaries

Such processes, however free from external gain or loss they may be, are in no sense of the word true adiabatics They obviously come under the heading of partially resisted changes and may usually be considered as cases of frictional flow

Most of the theories of reversibility and irreversibility which are so puzzling to beginners have their origin in the attempt to elucidate such cases as this—and the elucidation is at its best a little vague If however we adopt the same interpretation of "added" heat that we used above, it will exclude all processes that in any way may be considered as cases of friction, and, with this convention, the simple definition of what we may call the conditions of "adiabasis" can be used without any lengthy proviso or doubtful theory

It will be seen, then, that although the heat actually added or lost externally in any process



[To face page 30.

is not necessarily the same as the heat referred to above as "added" or "lost," the conditions as to what heat should be regarded as "added" for the purpose of inclusion as an area in a chart and what should be so regarded in defining the conditions of "adiabasis" form one and the same convention, and this convention embraces most of the useful part of those theories of reversibility which apply to adiabatic conditions as well as to areas on charts.

XIV. Adiabatic Lines on the $\psi - T$ Chart.

It will be noticed on the various $\psi - T$ diagrams given that the graph of any adiabatic expansion adds a vertical heat area exactly equal to the intercepted horizontal area that it cuts off.

This is obviously necessary to fulfil the conditions of "adiabasis" (see Fig. 4 *et seq.*). Adiabatics on these charts are therefore a series of parallel logarithmic curves with definitely increasing thermal inertia, along which it may be said that the heat given up in loss of temperature is equal to the energy incurred in the gain of this inertia, and this is what we might expect when it is realized that in an adiabatic expansion the internal energy lost is equal to the sum of the work done and the external energy gained.

That adiabatic conditions involve a natural increase in inertia during expansion and fall of temperature is borne out by the analogy of

Fig 1, and the case of the freely revolving disc For if in this case the speed of rotation is checked at any moment by some external means which cannot rapidly absorb kinetic energy, the system will tend to maintain its energy at the slower speed of rotation by an increase of rotational inertia, and the distinct changes of disposition which were observed at certain definite periods during the increase of energy will be found to tend to continue beyond their proper time, and actually to recur from a directly opposite cause when the speed of rotation is reduced

XV INCURRED THERMAL INERTIA OR DEGREE OF ADIABASIS

The importance of Adiabatic changes in Thermal performances makes it necessary or at all events desirable to have some means of recognizing and designating any particular change with reference to the various and more familiar conditions that it involves

Now an Adiabatic change may naturally start from any state or condition of the working substance and there are therefore an infinite number of such changes possible When once however any particular state or condition is chosen there can only one adiabatic change take place from or through it, and if therefore we can fix on any property or quantity peculiar to a particular state point and at the same time bearing some relation to the adiabatic

change with which such a point may become concerned, we shall be able to designate this adiabatic in terms of the property selected.

Now during any adiabatic change, the increase in thermal inertia is definite, and therefore a definite temperature will always involve a definite thermal inertia. Although therefore in general a given adiabatic has no definite thermal inertia to apply to the working substance without reference to a definite temperature, any one adiabatic can always be compared with any other by the difference in thermal inertia between any two points at the same temperature on both of them.

An adiabatic, therefore, may in this sense be said to have "rank" over another by the difference in inertia at corresponding temperatures, and this forms a convenient method of labelling any adiabatic or estimating on a direct measure what for lack of a better word we may call its **Degree of Adiabasis.**

By choosing a convenient temperature in fact, the "adiabasis" of any particular expansion may be measured by the thermal inertia incurred at that temperature as a datum, and this is how the adiabatics are labelled (or measured) on the charts of Figs. 3 and 4.

The Degree of Adiabasis or Adiabatic Rank of steam at any point or in any condition forms therefore yet another heat property, which may be defined as the thermal inertia that would be incurred by adiabatic expansion from that point down to the fixed datum temperature.

For purposes of convenience 32° F. is usually taken as the datum level of temperature and the rank is usually measured "above water at 32° F" rather than in absolute Inertia Rank, the rank of the water line where it cuts this temperature being taken as zero, and the numbers allotted for adiabatic rank on steam charts are nearly always allotted on this convention

XVI Entropy

This new measurement or property is such a useful one that it is referred to under a separate name, as **Entropy** and denoted by a separate symbol, ϕ, and this name or this symbol may therefore be substituted for "Incurred" Thermal Inertia, Degree of Adiabasis or Adiabatic Rank in the foregoing paragraphs

The Unit of Entropy is of course the same as the unit of thermal inertia ($q\ i$), since the quantity of entropy at any point is merely the thermal inertia that will be "incurred" at and from that point under the above definite convention, while for any change at constant temperature the increase of entropy actually is the increase in the thermal inertia

The Physical Significance of Entropy.—In everyday language entropy may be defined as that property of a body which measures its capacity for absorbing or acquiring heat in terms of the awkwardness which it incurs for turning that heat into work, just as thermal

inertia has been seen to be capable of a very similar definition.

The Numerical Significance of Entropy.—As a numerical example of the significance of entropy, take, say, 1 lb. of dry saturated steam at 200 lb. per sq. in. absolute pressure (temperature 381·5° F. or 842·5° Abs. F.). Expand it adiabatically as far as possible, and then exhaust it at constant temperature and pressure. Suppose the lowest pressure that can be reached is 5 lb. per sq. in. abs. (temp. 163·5° F. or 624·5° Abs. F.).

After adiabatic expansion to this temperature and pressure the total heat H * remaining in the steam (above 32° F.) is 963·5 B.T.U.

Again suppose that a final pressure of 0·5 lb. per sq. in. abs. (temp. 80° F. or 541° Abs. F.) can be reached.

The total heat H * remaining after adiabatic expansion to this temperature and pressure is 836 B.T.U. (above 32° F.).

In each case the heat remaining is the heat unavailable for work, and it is seen therefore

* The total heat can be calculated from the final volume of the steam as determined by the P.V formula for adiabatic expansion, viz:—$P.V^{1\cdot135} =$ Constant. The formula however is not altogether reliable and its derivation is not discussed here.

In the above cases the final volumes are 60·8 and 477 cu. ft. respectively, and the dryness fractions (from the known volumes of dry saturated steam) are 0·832 and 0·745. Hence (from the formula $H = S + xL$) we arrive at the values 963·5 and 836 B.T.U. as given above. The calculation is a good illustration of the saving of labour afforded by the use of steam charts, since instead of calculation the total heat might have been read off directly from a chart and a more reliable result arrived at.

that for the particular expansion chosen (the adiabatic passing through the original state point taken) the unavailable heat at an exhaust temperature of 624·5° Abs. is 936·5 B.T.U., while that for an exhaust at 541° Abs. is 836 B.T.U.

Now although the exhaust temperatures were chosen quite at random in these two cases, it will be found that the ratio of the unavailable heat to the absolute temperature is the same in each, i.e. that 963·5/624·5 = 836/542 = 1·51.

This ratio, i.e. "the unavailable heat (above 32° F.) per absolute degree of exhaust temperature," is therefore a constant quantity for all points along the adiabatic.

It is in fact the quantity that we have already defined as the thermal inertia incurred (at 32° F.) in a definitely specified process.

Entropy, then, as we have seen, always measures the unavailable heat (from 32° F.) per absolute degree of the lowest temperature reached in a particular adiabatic expansion

XVII. Inevitable or "Incurred" Waste.

Now since an adiabatic change is essentially one which wastes the minimum amount of the original stock of heat, the unavailable heat, after adiabatic expansion, is the minimum possible waste.

Entropy therefore measures the minimum possible waste per absolute degree of the lowest

available temperature, and the increase of entropy in any process, if multiplied by the lowest available ABSOLUTE temperature, gives the irreducible minimum of waste inevitably and unavoidably "incurred" in the particular process in question, and this is another way of looking at Entropy or incurred Thermal Inertia.

The waste incurred will of course be given as total heat "from 32° F.," with any total entropy measurement, and with such measurements therefore, in dealing with ordinary feed temperatures, a certain amount of sensible heat must always be deducted.

If increase of entropy is dealt with, this point does not however arise, as increase of entropy is naturally independent of datum level.

The idea of minimum waste involves a most important aspect of entropy, and the aspect with which it is perhaps most frequently associated. The word entropy itself means "a turning away," perhaps not altogether unsuggestive of "shame," and the same idea is often associated with "awkwardness," a word that we have also introduced in connection with entropy.

In whatever aspect we look at it however, it is a property which it is very convenient to work with, and for this reason it is embodied in some form in almost all working charts, and it is one of which it is therefore most important to have some real physical conception.

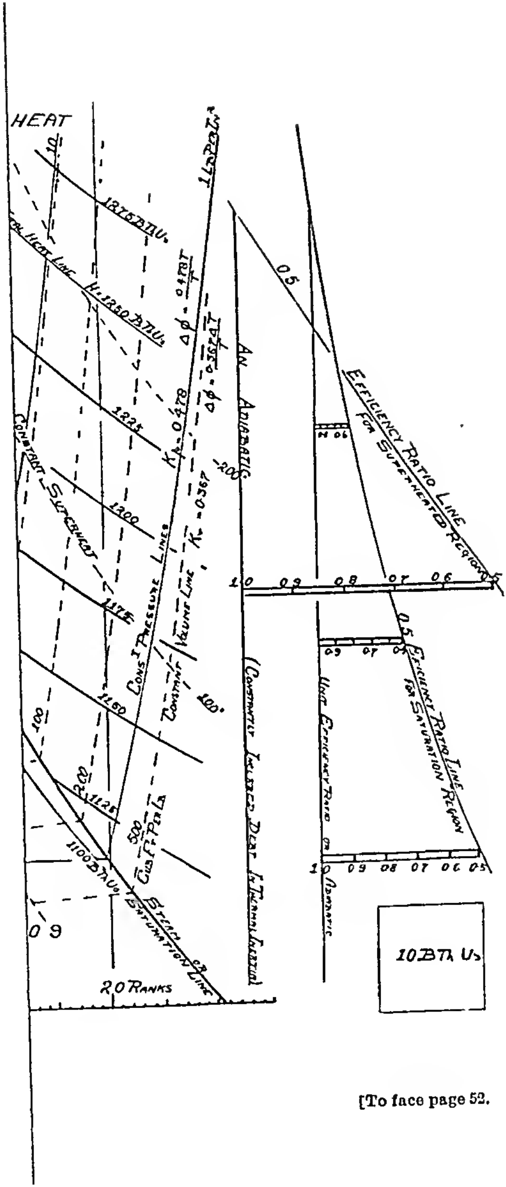
XVIII Entropy Charts and Diagrams

In the majority of charts entropy is embodied as one of the co ordinate axes, and this is easily done since all points on any adiabatic, as we have seen, have equal entropy Entropy moreover involves no new idea, being merely the thermal inertia involved in a particular process

In any such chart in fact, adiabatics being isentropics are merely a series of straight lines parallel to the other co ordinates, and the entropy, as we have seen, is merely the rank of these adiabatics It is easy therefore to imagine an entropy chart as being developed from any other chart containing adiabatic lines by a sort of geometrical distortion which will make all these lines parallel to an axis, and those of equally increasing rank equidistant from each other

The Entropy — Temperature Diagram or $\phi - T$ chart of Fig 9 may be imagined as merely a distorted $\psi - T$ chart in which the lines are sheared across in such a way as to make adiabatics vertical The derivation of the one from the other is shown in Fig 10, and it is seen that constant thermal inertia lines on the $\phi - T$ diagram slope forward at every point exactly as much as in the $\psi - T$ diagram the adiabatics slope back

Constant thermal inertia lines on the $\phi - T$ diagram are equidistant and parallel logarithmic curves, just as are adiabatics on the $\psi - T$



[To face page 52.

chart, and therefore the area vertically under a constant thermal inertia line in the one chart will correspond to the area vertically under an adiabatic in the other, and vice versa.

Now the heat added or rejected at constant thermal inertia is given on the $\psi - \mathrm{T}$ diagram by the horizontal area Q′, and must therefore be given by an equal area on the $\phi - \mathrm{T}$ diagram, the units on the axes of the two diagrams being the same.

In adiabatic expansion however the horizontal area Q′ of the former chart has been seen to be equal to the vertical area Q (the heat actually "added" being nil), and therefore, since the area under the adiabatic for one chart corresponds to the area under the constant thermal inertia line for the other, the heat actually added for a change at constant thermal inertia will always be given on the $\phi - \mathrm{T}$ chart by the single vertical area (corresponding to Q) under the path representing the change.

Now this will be found to be the case for all changes on this diagram, i.e. the single complete vertical area below the path will always (subject to the general conditions which are applicable to all charts) give the actual added heat.

In symbols therefore $\Sigma \mathrm{T} d\phi$ is always equal to Q, whence $d\phi = \frac{d\mathrm{Q}}{\mathrm{T}}$ or $\phi = \Sigma \frac{d\mathrm{Q}}{\mathrm{T}}$, and this is the mathematical definition of entropy.

It is seen that in an adiabatic expansion ϕ is constant, and therefore $\mathrm{T} d\phi = d\mathrm{Q} = 0$, which is the mathematical definition of "adiabasis."

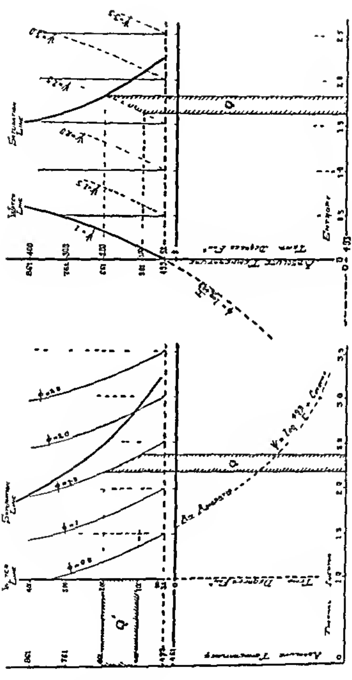


FIG 10 —DERIVATION OF $\phi - T$ CHART FROM $\psi - T$ CHART

the interpretation of Q being understood to be limited by the conditions referred to above.

Any enclosed area on the $\phi - T$ *chart* is a work area just as it is on the $\psi - T$ chart, and for the same reason all corresponding enclosed areas on the two charts are in fact equal.

The area under a path is of course equal to the sum of the corresponding added vertical and intercepted horizontal areas (Q and Q′ of Fig. 10) on the $\psi - T$ chart.

In an adiabatic change this area is obviously nil on the $\phi - T$ chart, since ϕ is constant and the path is therefore vertical.

This is what might naturally be expected, since the heat added in such a change is nil, and as was seen in the $\psi - T$ chart, the horizontal area subtracted is equal to the vertical area added in the process.

The water line on the $\phi - T$ chart is a line of definitely increasing entropy, and this also is only what might be expected since $\phi = \Sigma \frac{dQ}{T}$. In any rise of temperature along this line in fact a definite rise of thermal inertia is always "incurred" in the sense in which we have already used the word, even though the amount "incurred" is not everywhere the same.

The actual thermal inertia is of course constant (as shown on the $\psi - T$ chart), but the inertia incurred by adiabatic expansion from any point to the datum level depends on the point chosen, and is in fact given by the quantity $\Sigma \frac{dQ}{T}$, i.e. by K $(\log T - T_0)$, or actually $\log_e T/493$,

since K (the specific heat) = 1, and T (the datum temperature) = 493° F. Abs., and this is how lines of constant thermal inertia on this chart (and adiabatics on the $\phi - T$ chart) come to be parallel logarithmic curves.

The dry-saturation line is a sloping curve very similar to that of the $\phi - T$ chart, and serves the same purpose.

Lines of constant temperature are of course identical. Since adiabatics are straight and parallel, this chart is very convenient to work with, and this advantage applies to any chart of which entropy forms a co-ordinate.

Any change whatever should of course be capable of representation on any complete chart, and it may be useful for purposes of comparison to consider the representation of some well-known cycles of operation on each of the charts described above.

XIX. The Thermal Performance in Two Well-known Cycles of Operation.

Two of the most typical and most widely known cycles of operation for the working substance in a heat engine are Rankine's and Carnot's cycles. The former of these is particularly applicable to the steam engine, and the latter of more general application.

In Rankine's Cycle the engine is supposed to use the steam supplied from a boiler; to expand it adiabatically down to the lowest available

condenser temperature after the supply from the boiler has been cut off; then to exhaust and condense it at that temperature, and eventually to use it again after its temperature has been raised to the boiling-point and evaporation has been carried out under the same conditions as before.

In Carnot's Cycle the working substanee may be anything capable of sufficient expansion, and the engine uses it by taking in heat at a constant temperature with the necessary isothermal increase of volume; then expanding it adiabatically after the supply of heat is cut off till the lowest available temperature is reached; rejecting the remaining heat at that temperature by isothermal decrease of volume, and finally compressing it adiabatically until the temperature is reached at which it receives heat and at which point the process may start again.

A steam engine working on Carnot's Cycle would have to complete its condensation by adiabatic compression, which would not be generally convenient in practice, and for this reason the Rankine Cycle is the one used in the consideration of the theoretical thermal performance of the steam engine, while Carnot's Cycle is of not much more than academical value in such a case.

It should be useful however to compare the operations of each of these cycles, particularly if some real conception can be obtained of their physical import and significance, and this can be done with more or less completeness by

devising a suitable mechanism, and illustrating the performance in each cycle by some easily conceived mechanical analogy.

XX A Mechanical Conception of a Complete Thermal Performance

The mechanism illustrated in Fig 11 affords perhaps a fair parallel to the real behaviour of the working substance in an engine, and it illustrates the difficulty and indirectness in the exchange of heat for work, as well as the change of inertia that accompanies it

The arrangement consists of a short shaft carrying a pair of heavy "governor" balls mounted on bell-crank levers controlled by varying tension springs, and forming the parallel to the actual working substance

An electric motor or prime mover A and a special brake B capable of being applied at will form the parallel to the source and sink of heat, i e to the boiler and condenser respectively in the case of a steam engine, while a straight ram C controlled by the short ends of the governor levers, and a varying and artificially variable compression spring forms the parallel to the engine itself

The device does not exactly form a "synthetic gas or steam," but it reproduces with a fair degree of accuracy the sort of changes that must occur, not only in the rejection of heat at exhaust, but in the original acquisition of heat

in the formation and admission of the steam or gas, as well as in its subsequent expansion, and what is more important, the actual performance of work as the changes take place. It gives in fact a very fair analogy to the behaviour of the working substance under any such conditions as those by which we are likely to want

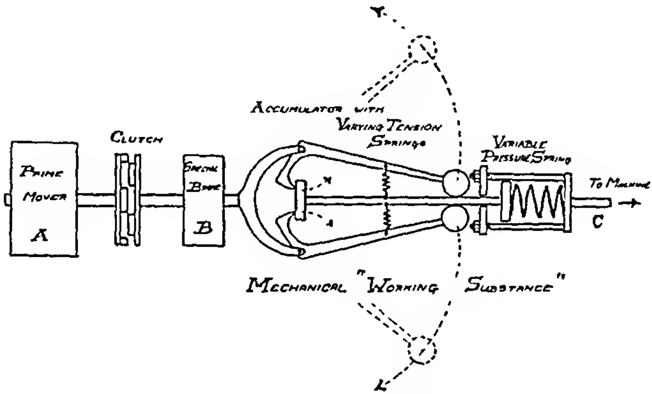


FIG. 11.—MECHANICAL CONCEPTION OF WORKING SUBSTANCE IN A HEAT ENGINE.

to control it, and can be used to illustrate either of the working cycles referred to above.

The changes in the energy of the revolving weights and their rotational inertia can be plotted against half the square of their speed to obtain the work done, etc., so as to produce in each case a diagram which will illustrate the corresponding changes in heat energy, temperature, and thermal inertia as plotted on a $\psi - T$ chart, and will compare with those of

the corresponding $\phi - T$ chart, in the manner outlined above

The changes in the two selected cycles of operations with their equivalents in the mechanical analogy are briefly outlined below, and illustrated in the diagrams of Figs 12 and 13, which can be regarded either as representing the rotational inertia mk^2 of the mechanical "working substance" plotted against half the square of its rotational speed ω, or as the thermal inertia ϕ of the actual working substance plotted against its temperature T in the manner of the $\phi - T$ diagrams above while Figs 12A and 13A represent the entropy changes plotted in a similar way

XXI An Illustration of Two "Mechanical" or Thermal Cycles as they would appear on Diagrams or Charts

(A) The usual Steam Engine Cycle (Rankine's Cycle, Fig 12)

This consists of (1) heating the feed water, (2) turning it into steam at constant pressure, (3) expanding it adiabatically to the lowest available temperature, and (4) exhausting at constant temperature The analogous operations in the mechanical parallel are briefly tabulated under the different headings below The method of plotting the diagram is that of Fig 2, etc, above

(1) *Heating the Feed Water.*—Clutch in, brake off, shaft speeded up at constant mk^2 from ω_0 to ω_1; weights retained by tension and compression springs, no motion of ram, the spring compression being increased as necessary to

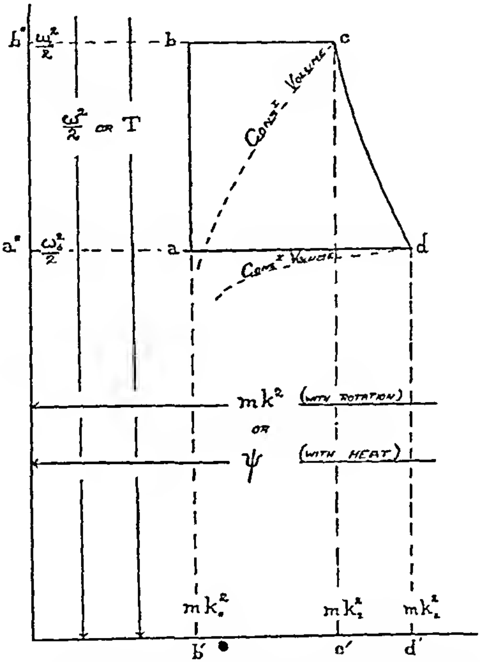


FIG. 12.—IDEAL STEAM ENGINE CYCLE (WITH THERMAL INERTIA OR ROTATIONAL ANALOGY).

correspond with the rise of pressure at the boiler.

Path on diagram ab; heat or energy added $abb''a''$, in Fig. 12, or $a'abb'$ in Fig. 12A. Work done nil.

(2) *Isothermal Formation of Steam* —Clutch in, brake off, weights flying out, mk^2 increasing from mk_0^2 to mk_1^2, and pushing out ram against

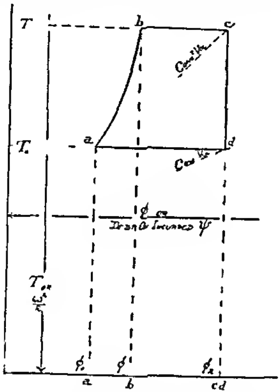


FIG 17A —IDEAL STEAM ENGINE CYCLE (WITH ENTROPY OR INCREASED THERMAL INERTIA)

constant pressure, shaft maintained at constant speed ω_1 by prime mover

Path on diagram bc, heat or energy added $b'bcc'$, work done measured by amount rod moves against constant pressure, or by amount

cut off from $b'bc$ on diagram by constant volume line through c.

(3) *Adiabatic Expansion.*—Clutch out, brake off, weights still flying out, mk^2 increasing from mk_1^2 to mk_2^2 against decreasing pressure on ram, speed of shaft falling from ω_1 to ω_0.

Path on diagram cd; heat or energy added nil (area $c'cdd'$ being equal to $b''baa''$); work done measured by combined movement of rod due to extension of spring and outward movement of weights, i.e. area cut off from $b'bcd$ by constant volume lines through c and d.

(4) *Isothermal Exhaust.*—Clutch out, brake on, weights being pushed in by ram mk^2 decreasing at constant (reduced) pressure to its original value mk_0^2 speed of shaft kept down to ω_0 by special brake.

Path on diagram da; heat or energy rejected $dd'b'a$, in Fig. 12, or $dd'a'a$ in Fig. 12A. Negative work done measured by movement of ram at constant low pressure against ends of levers, i.e. area cut off from $b'ad$ by constant volume line through d.

The total heat or energy added during the cycle, i.e. from a to d, is therefore the area $b'bcdd'$ in Fig. 12 and $a'abcd'$ in Fig. 12A, while the total heat or energy rejected in going from d to a is the area $b'add'$ or $a'add'$ in Fig. 12A.

The total work done is therefore the enclosed area $abcd$, and these are the work and energy area not only in this mechanical analogy, but also in actual practice.

(B) Carnot's Cycle (Fig 13)

This consists of (1) Adiabatic Compression, (2) Isothermal Expansion taking in heat, (3)

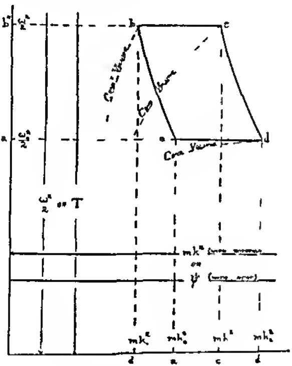


FIG 13 CARNOT'S CYCLE (WITH THERMAL INERTIA OR ROTATIONAL ANALOGY)

Adiabatic Expansion, and (4) Isothermal Compression or Rejection

With the exception of (1) and (4) the operations representing these changes either in the mechanical analogy or in the actual working

substance are the same as in the case of the Rankine Cycle above.

In (4) however the rejection of heat to the condenser, or kinetic energy to the brake, is

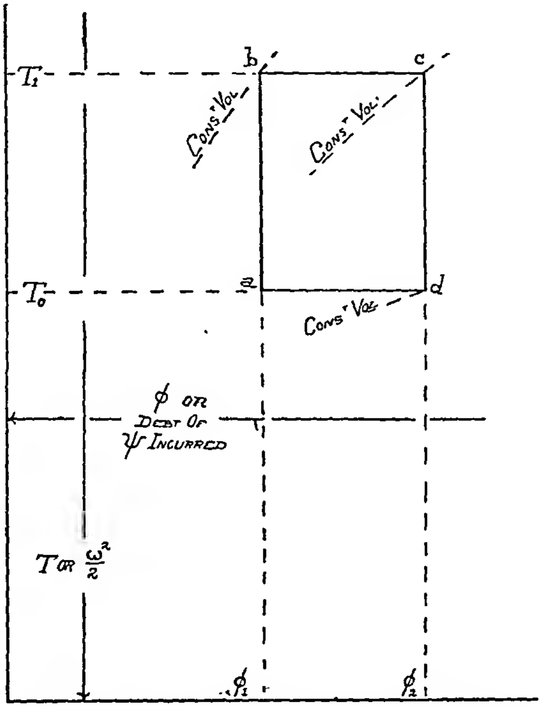


FIG. 13A.—CARNOT'S CYCLE (WITH ENTROPY OR INCURRED THERMAL INERTIA).

stopped short before the inertia has been reduced to its lowest value (e.g. at mk_3^2 instead of mk_0^2), and is reduced to mk_0^2 by compression instead of by rejection of heat.

In operation (1) therefore for the Carnot Cycle the mechanical analogy is :—

Clutch out, brake off, weights being pushed in by ram at increasing pressure, speed of shaft allowed to rise from ω_0 to ω_1, while mk^2 is reduced from mk_1^2 to mk_0^2.

Path on diagram *ab*; heat or energy added nil (negative vertical area = positive horizontal area in Fig. 13), negative work done measured by movement of ram at increasing pressure, i.e. area cut off from *baa″* by constant volume line through *b*.

The total heat or energy added during this cycle is the area *b′bcc′*, and the total rejected is *a′add′*, while the work done is the enclosed area *abcd*.

The efficiency of the cycle is therefore slightly higher than that of the Rankine Cycle, though the difference is not very great.

Similar cycles could of course be plotted on the H.T. chart of Fig. 3, and indeed on any other chart, and the derivation and dependence of the various charts from and on each other could easily be visualized by the distortion of the corresponding diagrams.

XXII. Diagrams and Charts in General.

The actual development and formation of charts is of course carried out by copying or plotting such quantities as are required on to any desired axis, and the geometrical distortion

referred to above and indicated in the foregoing analogy as a rule is only imaginary. It serves to illustrate an important fact however, viz. that a new chart is not necessarily a representation of a new idea. Any one chart in fact may as a rule be converted into any other as convenient, and if the original is complete, the new one should involve no fresh calculation, nor even any explanation. It is only necessary in fact to transfer the various quantities from the original to the new one, keeping the required quantities as co-ordinates, and a new chart will be obtained as desired.

The Entropy—Total Heat Diagram or $\phi - H$ chart is one in which the entropy is plotted against total heat. The area in this diagram has no useful significance, but the advantage of having the total heat lines straight and parallel is a convenience which more than compensates for this, particularly in turbine work.

Efficiency ratio lines (which are explained below) are easily plotted on this diagram, lines of zero and unit efficiency ratio both being straight and parallel to the respective axes.

The chart as used in common with many others usually consists of only that part of the complete diagram including just the region round the saturation line, this region being that almost invariably required in practice.

Other Charts.—Various charts have been made and used which are not described above, among the best known of these being Morrow's Total

Heat – Volume Diagram, and Mollier's Total Heat – Pressure (or H – P) Diagram

Both of these diagrams as a rule only deal with the region round the saturation line In neither of these however is the area used, and in neither of them naturally are adiabatics either parallel or straight Morrow's chart adopts a logarithmic system of ruling, and is sometimes very convenient for turbine calculations owing to the ease with which the volumes can be read off Mollier's H – P diagram is much used except to replace steam tables

The volume – pressure diagram is occasionally used as a chart, and in this case, except with "imperfect" expansions, the area can be used as well Entropy – pressure and entropy – volume diagrams appear hardly to be used at all

The comparative advantages of the different charts discussed can best perhaps be seen by tracing a few typical expansions and changes on them, and noting the ease and convenience with which this can be done

XXIII. A Few Distinctive and Extreme Expansions as they Appear on Various Charts

I. Adiabatic Expansion

The standard, and at the same time ideal expansion with which to compare all others, is of course adiabatic expansion, and this, as we have seen, follows a line of constant entropy

or permanently incurred thermal inertia from whatever point it starts.

In $\phi - T$ or $\phi - H$ charts, or in any chart in which ϕ is the principal axis, an expansion is therefore always represented by a straight line parallel to the vertical ordinate, and can be put in directly from any point we like to name by a line perpendicular to the abscissa.

In other charts, unless one of the "incurred thermal inertia" or "entropy" lines already on the chart happens to pass through the exact point in question, any required adiabatic expansion will have to be interpolated between the two nearest of these lines that are actually given.

From this point of view, then, the $\phi - H$ and $\phi - T$ charts are better than the $\psi - T$ chart and much better than either the $V - H$, $P - H$, $H - T$, or $P - V$ charts, since even if these charts contain a fair number of adiabatic lines, the ones to be interpolated will not as a rule be straight.

II. Dry Saturated Expansion.

This of course can only start from a point on the Steam or Saturation Line, and must follow this line at all points. This line is always included in working charts, and such an expansion therefore is as easily represented on any one chart as on any other.

III. Expansion with Constant "Total Heat."

This must follow a line of constant "Total

Heat," and is therefore represented with equal ease on either the $\phi - H$, $H - T$, $V - H$, or $P - H$ charts In the $\phi - T$, $\psi - T$, and PV charts, unless the particular expansion required is already plotted, it will have to be interpolated between adjacent "Total Heat Lines" that are already there, just as adiabatic lines have to be interpolated in all these except the $\phi - H$ and $\phi - T$ charts

IV Isothermal Expansion

In the case of a perfect gas this expansion is the same as an expansion with constant "Total Heat," since from the energy equation, $PV = CT$, both internal and external energy are constant

In the regions of extreme superheat it may therefore be regarded as very nearly the same as Expansion III above, since in this case steam is very nearly a perfect gas In these regions therefore it can be dealt with almost equally well by any of the above charts or even by a $P - V$ chart, since in this case it gives us the well known and well worn "hyperbolic" expansion

For all conditions in or around the saturated region however, actual isothermal expansion is very different from an expansion with constant "Total Heat" In such a case it is of course most easily dealt with by the $\phi - T$, $\psi - T$, or $H - T$ charts, since in these cases it is a straight line parallel to the abscissa

Such an expansion however is rarely met in these regions in practice, and if it is it must be

interpolated between given constant temperature lines in any chart in which temperature is not chosen as an axis.

XXIV. Conditions Producing the Above Expansions.

A true adiabatic expansion, whether resisted or not, requires, as we have seen, no "gain" or "loss" of heat. The other expansions, in the order in which they are given, require the supply of increasing quantities of heat to produce them, i.e. IV requires more then III, and III more than II, and II of course more than I, since I is an adiabatic.

Now if these expansions are "resisted" (i.c. if they are all opposed at every point by an external pressure sensibly equal to the internal) the supply of heat required to produce them will have to be external, since increasing amounts of work are done in each successive case.

If however the expansion is "unresisted," we can no longer say that the work performed is increasing in successive cases, and that an increasing supply of external heat is required.

As a matter of fact, in unresisted expansion any of these cases which do not involve an increase in "Total Heat" may be produced without any addition of external heat at all. In such a case the addition of heat must be internal, such as is produced by friction, and therefore at the expense of some of the heat

of the steam that might otherwise have been turned into work or K E

Such a state of things almost invariably obtains to a greater or less degree in practice

In "resisted" expansion we may perhaps occasionally add jacket steam to produce a higher expansion, but this is only very rarely done, and in any case an "unresisted" expansion which is "higher" than the adiabatic is almost invariably produced by friction, i e at the expense of the heat available in steam instead of by jacket heat, and therefore not only entails more waste than the adiabatic, as is the case in resisted expansion, but actually produces less K E

The loss of heat available in the steam in "imperfectly unresisted expansion is as we have seen, exactly equal to the heat that has to be added externally in the jackets in the corresponding case of perfectly resisted expansion, and this is considerable in case II, while in case III it is equivalent to the whole of the K E available from the expansion and hence produces in unresisted expansion the phenomenon known as ' wire drawing when no heat at all is turned into K E, and the total heat is constant In case IV, unless we are dealing with a perfect gas when III and IV are identical, the loss of available heat is so great that it cannot even be supplied by the heat which the body carries with it, and the total heat would actually have to be increased in order to produce it Such a case, if unresisted, therefore would

be more absolutely wasteful than even case III of wire-drawing as given above.

Expansions likely to Occur.—In practice it is quite unusual to employ jacket steam, and therefore with resisted expansion, neglecting the effects of cylinder condensation and radiation losses, the case that is most likely to occur is more or less approximately near the actual adiabatic. Actually the effects of cylinder condensation and radiation are more often than not considerable, and the real approximation to the adiabatic may therefore be very slight.

There is however no other simple assumption available for the usual resisted expansion, and for this reason it is generally taken as adiabatic on the understanding that it takes place without jacket heat.

In unresisted expansion, on the other hand, although the addition of jacket heat is still more unusual, we may without any such addition get anything from the true adiabatic to an expansion with constant total heat, or (if the steam is so superheated as to be regarded as a perfect gas) even an isothermal one, i.e. an expansion with constant temperature, and we therefore have an infinite number of cases of unresisted expansion available for consideration, all of them occurring without jacket heat or radiation loss and yet only one of them really adiabatic.

XXV Unresisted Expansions with Various Efficiencies and the Significance of Efficiency Ratio Lines

Although after any expansion and under any conditions the inevitable waste at exhaust is very large, this waste is from the nature of things unavoidable and in a sense not "available" for work There is therefore a sense in which an expansion is not in itself wasteful, since it may use all the heat that is really available for work Adiabatic expansion may in fact be regarded as typically non-wasteful in this respect, since it uses the whole of the "available" quantity, and this consideration is very valuable in comparing the efficiencies of various expansions that are likely to occur in practice, since in this sense we may regard the efficiency of the adiabatic expansion as unity or 100 per cent and that of wire drawing or constant superheat as zero

Such a measure of the comparative efficiency of an unresisted expansion is called its efficiency ratio, and is a measure of the proportion of the AVAILABLE heat that is conve ed into work in the expansion, the "availabl heat being understood to mean the heat th t is still available for work when the large inevitable waste that has been incurred in its supply (i e the product of the increase of mertia incurred and the lowest available temperature) has been deducted

Efficiency Ratio Lines may be drawn on a

chart representing "unresisted" expansions with various efficiency ratios, and this will enable us to compare amongst themselves the work value of actual expansions that may occur, and to neglect for the moment the total heat measurements which are apt rather to lead us to the conclusion that all expansions are so inefficient as to be hardly worth comparing at all. By following such lines in dealing with any particular problem, and assuming a ratio that from previous practice we have some reasons to expect, we can plot the expansion that is likely to occur in that particular case, and so read off the various volumes, pressures, temperatures and drynesses, etc., that have to be allowed for, as well as the work that we may reasonably expect to obtain.

The efficiency ratio lines on the $\phi - T$, $\psi - T$, and $H - T$ charts of Figs. 9, 4, and 3 form permanent guiding lines in this way, and an expansion of known or assumed efficiency may therefore be plotted on either of these charts from any starting-point by merely drawing a line parallel to the guiding line giving the particular efficiency ratio in question.

XXVI. The Justification for the Analogies Used.

The real significance of the efficiency ratio lines lies of course in the increase in thermal inertia as the efficiency ratio gets lower, and

this is such a useful significance that it is in itself a sufficient warranty for the adoption of the somewhat elaborate mechanical analogy which led up to it. This analogy, as we have seen, is often somewhat far-fetched, and occasionally not quite accurate, but if it enables us to retain a physical conception of the dimensions of the changes that occur in otherwise abstruse processes, it has served a purpose which will be none the less valuable for any slight discrepancies in the details actually conceived, and further than this, there is always the possibility that a modification of these details may lead to the conception of a mechanical analogy to thermal energy which will be absolutely accurate in all respects. The important thing however is to obtain a conception of the main dimensions of the changes taken place, and this has already been done. With such a conception charts, etc., may be used with ease and confidence and calculations made without that distrust which so often arises from complicated mathematical calculations the physical aspect of which is not even partially understood.

Printed in Great Britain by
UNWIN BROTHERS, LIMITED, THE GRESHAM PRESS, WOKING AND LONDON

Report
No.
65. Salt-Glazed Ware Pipes
66. Copper-Alloy Three-Piece Unions
67. Ceiling Roses
68. Steel Conductor Rails
69. Tungsten Filament Glow Lamps
70. Pneumatic Tyre Rims
71. Wheel Rims and Tyre Bands
72. Electrical Machinery
73. Two-Pin Wall Plngs and Sockets
74. Charging Plng and Socket
75. Steels for Automobiles
76. Tars, Pitches, Bitumens and Asphalts
77. Electrical Pressures (5d.)
78. Cast Iron Pipes (Water, Gas and Sewage)
79. Special Trackwork for Tramways
80. Magnetos for Automobile Purposes
81. Instrument Transformers
82. Starters for Electric Motors
83. Dope and Protective Covering for Aircraft
84. Screw Threads, British Standard Fine and their Tolerances
86. Magnetos for Aircraft Purposes
87. Air Screw Hnbs
88. Electric Cut-onts
89. Indicating Ammeters, Voltmeters, Wattmeters, Freqnency and Power Factor Meters
90. Recording (Graphic) Ammeters, Voltmeters and Wattmeters
91. Electric Cable Soldering Sockets
94. Watertight Glands for Electric Cables
95. Corrections to Effective Diameter of Whitworth Screw Threads
97. Watertight Fittings for Incandescent Electric Lamps
98. Goliath Lamp Caps and Lamp Holders
100. Body Spaces and Frame Ends
103. Falling Weight Testing Machines for Rails (5d.)
104. Light Flat Bottom Railway Rails and Fishplates
105. Light and Heavy Bridge Type Railway Rails
106. Electrically Heated Cooking Range
107. Rolled Sections for Magnet Steel
111. Wrought Steels for Aircraft
112. Cold Worked Steels for Aircraft
113. Sheet Steels for Aircraft
114. Valve and Valve Spring Steels for Aircraft
122. Milling Cutters and Reamers
131. Notched Bar Test Pieces
132. Steam Turbines for Electrical Plant
135. Benzol for Motor Fuel
136. Automatic Telephone Systems
139. Red Fir Wood Poles for Telegraph and Telephone Lines

INTERIM REPORTS.

C.L. 2582. Ball Journal Bearings for Automobiles (5d.)
C.L. 3750. French Metric Screw Threads for Aircraft Purposes (11d.)
C.L. 7270. Screw Threads, British Standard Whitworth and their Tolerances
C.L. 7271. Screw Threads, British Association with Tolerances
C.L. 8564. Rubber Tyres for British Standard Rims